Validation of atmospheric temperature profiles and electron densities derived from CHAMP radio occultation measurements during measurement campaigns at Andøya (69.28°N, 16.02°E)

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Summary

Several measurement campaigns took place at the ALOMAR observatory at Andøya, Northern Norway during July-November 2001 to validate ionospheric electron density and dry temperature profiles in the troposphere and lower stratosphere derived from radio occultation measurements of the low earth orbiter satellite CHAMP.

For temperature sounding, three balloons are released around GPS satellite occultation events that occurred inbetween a distance of 200 km around Andøya. At altitudes of 7–20 km the CHAMP profile shows a positive mean deviation increasing with height by about 1.5-2 Kelvin/10 km overlayed with variations of ±1 K when compared to the radiosonde. Taking into account the previous and following radiosonde ascents the mean deviation seems to be of systematic nature due to the occultation principle or the retrieval algorithm and the variations are related to geographical variations of temperature and to the horizontal averaging by the radio occultation technique.

During the period from mid July to mid August, four occultations for ionospheric soundings occurred. The values of the F2 layer calculated from the CHAMP derived electron density profiles are compared to the readings of the Alomar and Tromsø ionosondes for these times. Comparison shows that using the radio occultation technique electron densities of the maximum value layer are calculated inbetween the same order of magnitude as the ionosondes measurements, however, they overestimate it in the cases discussed here.

Zusammenfassung

Zur Validierung von Elekronendichte- und Temperaturprofilen, abgeleitet aus Radiookkultationsmessungen von CHAMP wurden im Juli-November 2001 mehrere Messkampagnen am ALOMAR Institut auf Andøya, Nordnorwegen durchgeführt. Zur Temperatursondierung wurden drei aufeinanderfolgende Radiosonden um den Zeitpunkt von Okkultationsereignissen im Umkreis von weniger als 200 km gestartet. Das hier diskutierte Temperaturprofil von CHAMP zeigt im Höhenbereich 7-20 km eine mit der Höhe zunehmende positive Abweichung von ca. 1,5-2 K/10 km mit Variationen um ±1 K verglichen mit dem Temperaturprofil der zum Okkultationszeitpunkt fliegenden Radiosonde. Der Vergleich mit den vorhergehenden und nachfolgenden Sondierungen lässt darauf schließen, dass die mittlere Abweichung durch systematische Fehler des Okkultationsverfahrens oder den Retrieval-Algorithmus bedingt sind, die Variationen jedoch durch die örtliche Abweichung und die horizontale Mittelung des Messverfahrens.

Während des Zeitraumes von Mitte Juli bis Mitte August ereigneten sich vier Okkultationen zur Sondierung der Ionosphäre. Von den abgeleiteten Elektronendichteprofilen werden jeweils die Werte der F2-Schicht mit den zur gleichen Zeit gemessenen Elektronendichten der Ionosonden auf Andøya und bei Tromsø verglichen. Der Vergleich zeigt, dass mit Hilfe der

Radiookkultaktionstechnik die Elektronendichtewerte der F2-Schicht in der gleichen Größenordnung berechnet, in diesen konkreten Fällen jedoch überschätzt werden.

1. Introduction

When GPS signals received by Low Earth Orbiter Satellites (LEO's) encounter atmospheric neutral gas density gradients or free electrons in the ionosphere this leads to a refractive index gradient. Therefore, the radio wave underlies ray bending and delays in phase, travel time and polarisation. Assuming spherical symmetry the excess phase delay or bending angle profile of the ray may be used to derive dry temperature as other neutral gas parameters with additional information by inversion techniques (Fjeldbo and Eshleman, 1965) and electron density profiles (Hajj and Romans, 1998 , Schreiner et. al, 1999).

Temperature profiles derived by radio occultation techniques are of increasing intrest for investigation of the upper troposphere and lower stratosphere. Compared to conventional measurement techniques like radiosondes this technique provides global coverage and mean values integrated over about 200 km (Rocken et al., 1997). It is suitable for long-term trend investigations of temperatures (Kursinski et al., 1997) and also for gravity wave activity in altitudes of about 5–30 km (Tsuda et al., 2000). Since the application of the method for this purpose is relatively new, the long term potential of such measurements is still subject of scientific interest. Quality and yield of the data are important criteria. First results from the GPS-MET experiment (Kursinski et al., 1997; Rocken et al., 1997), the CHAMP mission (Wickert et al., 2001), and from theoretical studies (Foelsche et al., 2001) reveal that errors below 1 Kelvin at the above mentioned altitudes are expected to be reached in the next future.

Ionospheric profiles can be derived by solving a system of linear equations of the link related total electron content (TEC) provided by CHAMP (Jakowski, 1999). Again, advantages of this technique are found in the global and continuous coverage. So an inexpensive tool can be provided for ionospheric profiling. Because Abel inversion technique is fundamentally based on the assumption of spherical symmetry of the refractive index, horizontal gradients or small-scale structures in the electron density distribution cannot be detected by applying this technique. Under conditions of high ionospheric activity, when strong spatial plasma density gradients occur, the retrievel is not recommended.

During four ionospheric occultation events during the measuring campaign from mid July to mid August data of the Andøya ionosonde and also of the Tromsø Dynasonde are available for comparison with CHAMP derived electron density. Therefore, the electron density at the height of its maximum value, NmF2 (electron density of the F2-layer peak) are considered for the CHAMP data validation here. It may be noted that the ionogramms during the four events did not indicate disturbed ionospheric conditions and therefore comparisons are reliable considering also geographical variations in electron density.

2. Results

2.1 Atmospheric sounding: Validation of tropospheric and stratospheric dry temperatures

Three balloons were launched consecutively around the occultation event of November, 11, 2001 near Andøya (69.28° N, 16.02° E). The balloon ascent one is centered at about 16 km during the occultation event. The mean tangent point of the occultation appeared at 70.2° N, 12.0° E, with a distance of about 182 km. In Figure 1a the temperature profile from the the second balloon is shown together with the temperature profile derived from CHAMP for the altitude range 0-30 km and the results of the first and third balloon flights are shown in Figure 2a, respectively. The first balloon was the only one that reached up to nearly 30 km. The second and the third one boosted at about 20 km. Therefore the direct comparison between CHAMP and the second sounding is restricted to altitudes below that height.

Inspecting Figure 1a it is obvious that temperatures below 5 km are not comparable since the deviation becomes larger than 5 K. This is in correspondence with first results from CHAMP reported by Wickert et al. (2001), and is due to the increasing influence of water vapour below this altitude that is not taken into account in the retrieval of the dry temperature. Figure 1b shows the temperature difference between CHAMP and the radiosonde. The radiosonde temperatures are interpolated on the equidistant vertical grid of the CHAMP data that are equally spaced by 200 m. The solid curve shows the linear interpolation between the radiosonde values at these altitudes and the dotted curve shows the average value of the adjacent 5 measurements extending over a distance of about +/-100 m. It is found that the differences between these different interpolation methods are small. Therefore only the average value is considered in the following.

At 7-8 km, the height where the tropopause is located, the differences between the temperatures measured by the radiosonde and CHAMP become smaller than 2 K. Water vapour becomes negligible small for the retrieval of dry temperature there. Above 8 km the balloon sounding shows positive temperature deviation in the whole measuring range. The linear interpolated mean deviation increases by 1.5-2 K/10 km. This increase seems to be a systematic bias.

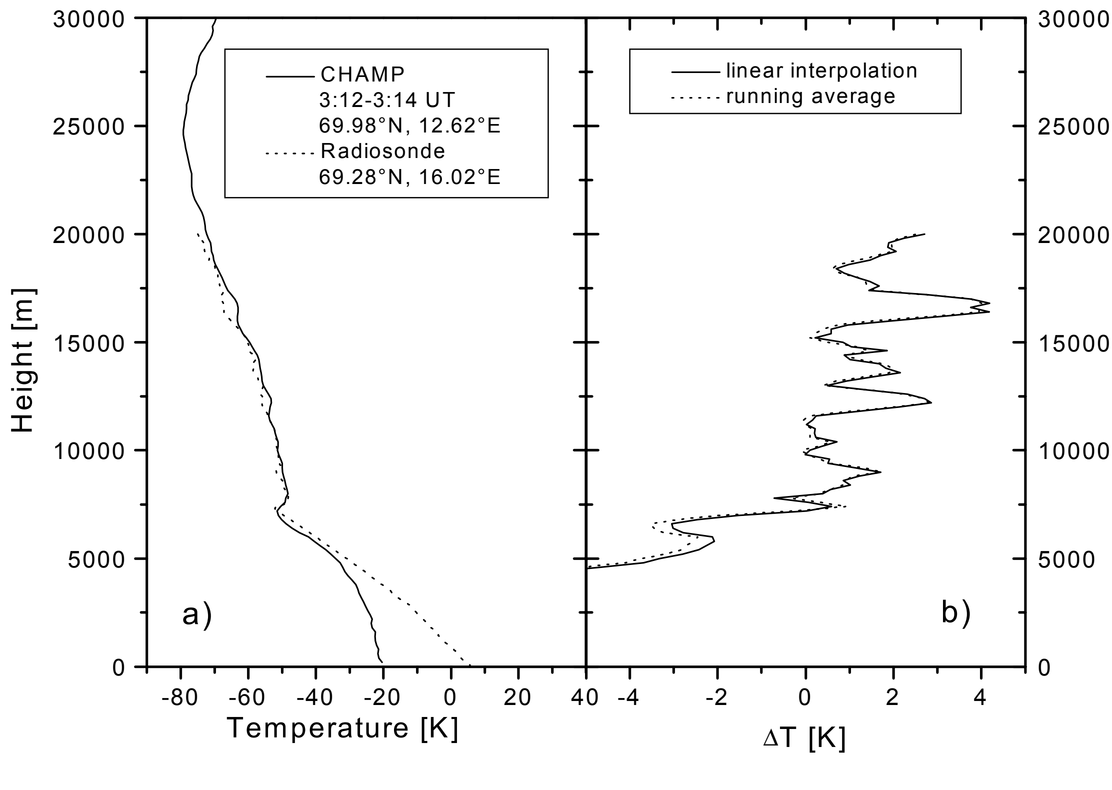

Figure 1: Temperature profiles derived from radiosonde and CHAMP occultation measurement (a) and difference between this two profiles (b).

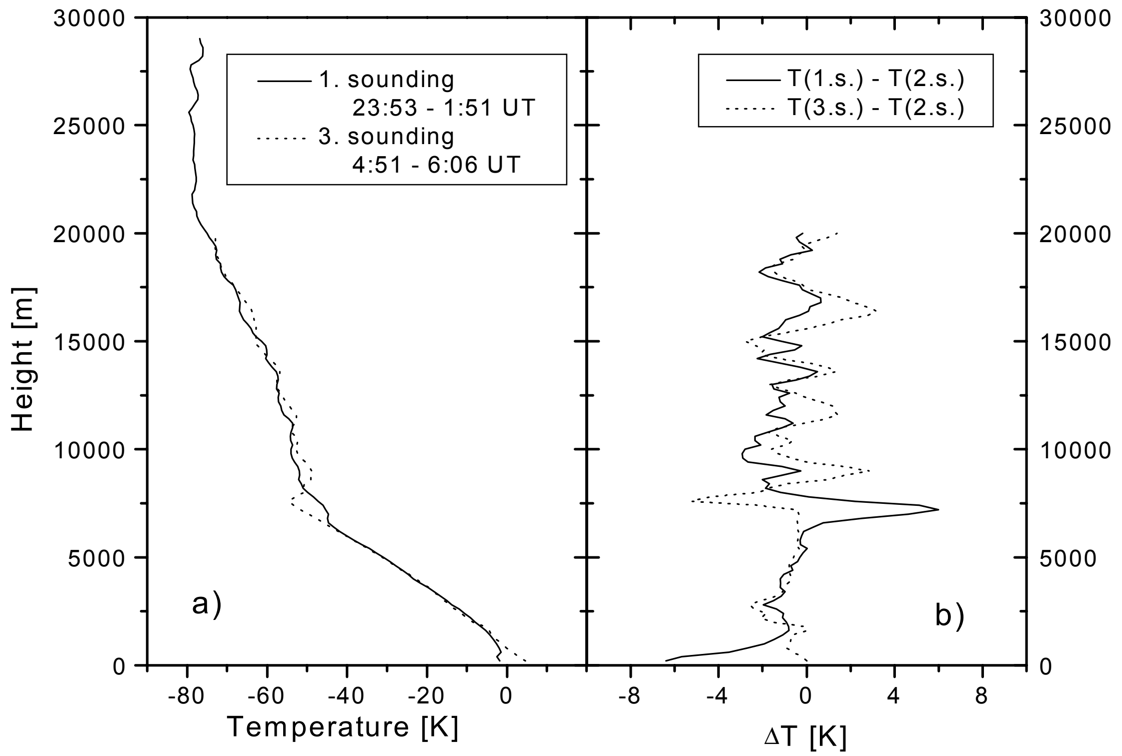

Figure 2: Temperature profiles from the first and third balloon soundings (a) and differences when compared to the second one (b).

The variation of the temperature deviation is in the order of about 1 K around the mean value. This is equivalent to the variations when compared with the precedent and subsequent sounding as shown in Figure 2b.

The deviations of the first sounding and the third sounding are strongest at the tropopause heights, being more than about +6 K for the first balloon and about –5 K for the third balloon. At altitudes between 8 km and 20 km the deviation is in most of the region in the range of ±1K.

The first balloon is launched about 2½ hours before the second one and the third one another 2½ hours later. During one time interval the air mass moves by a similar distance as the horizontal distance of the occultation point. The temperature difference between the different balloon soundings is either due to advection of air mass or to local temperature variations, e.g., from gravity waves. The soundings are all performed during November at night or early morning so no daily variability appears. Since the occultation measurement averages over the horizontal inhomogeneities the deviations from the balloon sounding in the CHAMP temperature profile could be explained thereby. The variability found in the CHAMP temperature profile therefore is not increased by noise from the measurement system.

2.2. Ionospheric sounding: Validation of F-region peak electron density

Ionosondes are independent measuring instruments that provide, besides ionospheric basic research data, also good opportunities for validating new systems. Frequencies between about 1 - 20 MHz are emitted by the ionosonde transmitter. The time interval from transmission to reception of a single frequency gives information about the virtual height of the corresponding electron density layer where the frequency is reflected. The radio wave travers regions of low electron densities and is absorbed by higher electron densities. Results are given in so-called ionogramms. In any case, exept for strongly disturbed ionospheric conditions with very high absorbtion of radio waves, ionogramms shows a critical frequency for the F2-layer (FoF2), which gives information about the peak electron density of the ionosphere.

The corresponding electron density (NmF2) is related to the critical frequency through Eccles refraction law:

$$NmF2 = 1.24 * 10^{-2} (FoF2)^2,$$

where the frequency is given in Hz and the electron density in electrons/m³.

During the campaign in August, 2001 four passes of the CHAMP satellite occured inbetween a cycle distance of 8° around Andøya where a CADI ionosonde is situated. For that time ionogramms of the Tromsø Dynasonde at 69.58°N and 19.22°E are also available for comparison.
In Figure 3 the location of occultations and ionosondes are shown. For comparison we chose occultations that did not necessarily lie directly near the ionosondes because occultation events are spread all over the globe and so only low chance is given that events occur at a certain location in a certain interval of time.

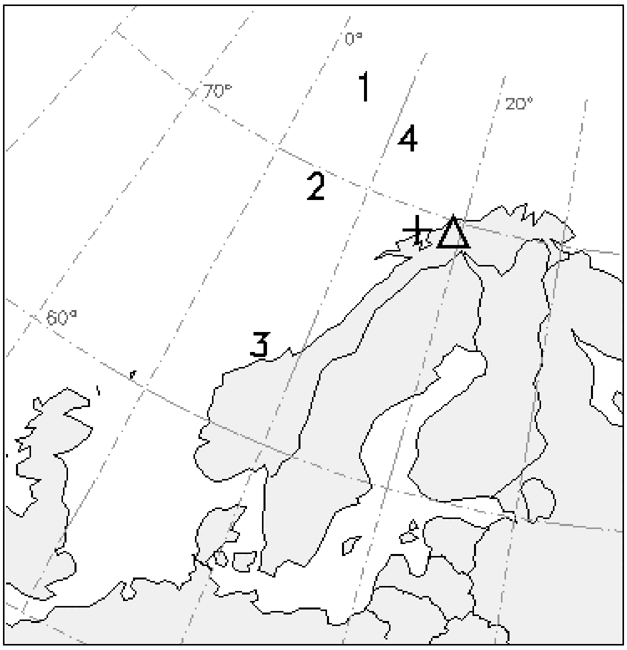

Figure 3: Locations of Andøya (plus) and Tromsø (triangle) ionosondes and occultation events.

In Figure 4, times of the events are given, together with the NmF2 measured by the Andøya and the Tromsø ionosondes as well as derived from the respective CHAMP sounding are displayed. A first inspection of the Figure shows that for all four events CHAMP estimates the NmF2 in the same order of magnitude, but slightly higher than they have been measured by the ionosondes. The values of electron densities of about $4-5*10^{11}$ electrons/m³ do not indicate high ionospheric activity. For all events both ionosondes measured rather similar NmF2 so that the ionosonde values seem to be reliable and very strong horizontal gradients as it is usual for high ionospheric activity can be ruled out. By taking into account typical geographical differences in electron density one can compare the ionosondes and CHAMP NmF2 for these events.

For event 1 and 4 CHAMP measured similar densities compared to the ionosondes. Referring to Figure 3 these two occultations are situated in the north of Andøya and Tromsø. Considering that electron density normally decreases polwards these two values seems to be overestimated. Event 2, which occurred in a similar latitude as the ionosondes display a too high NmF2 value, too. The more southerly lying occultation 3 shows also a too high NmF2, but it has to be taken into account here that electron density increases equatorwards.

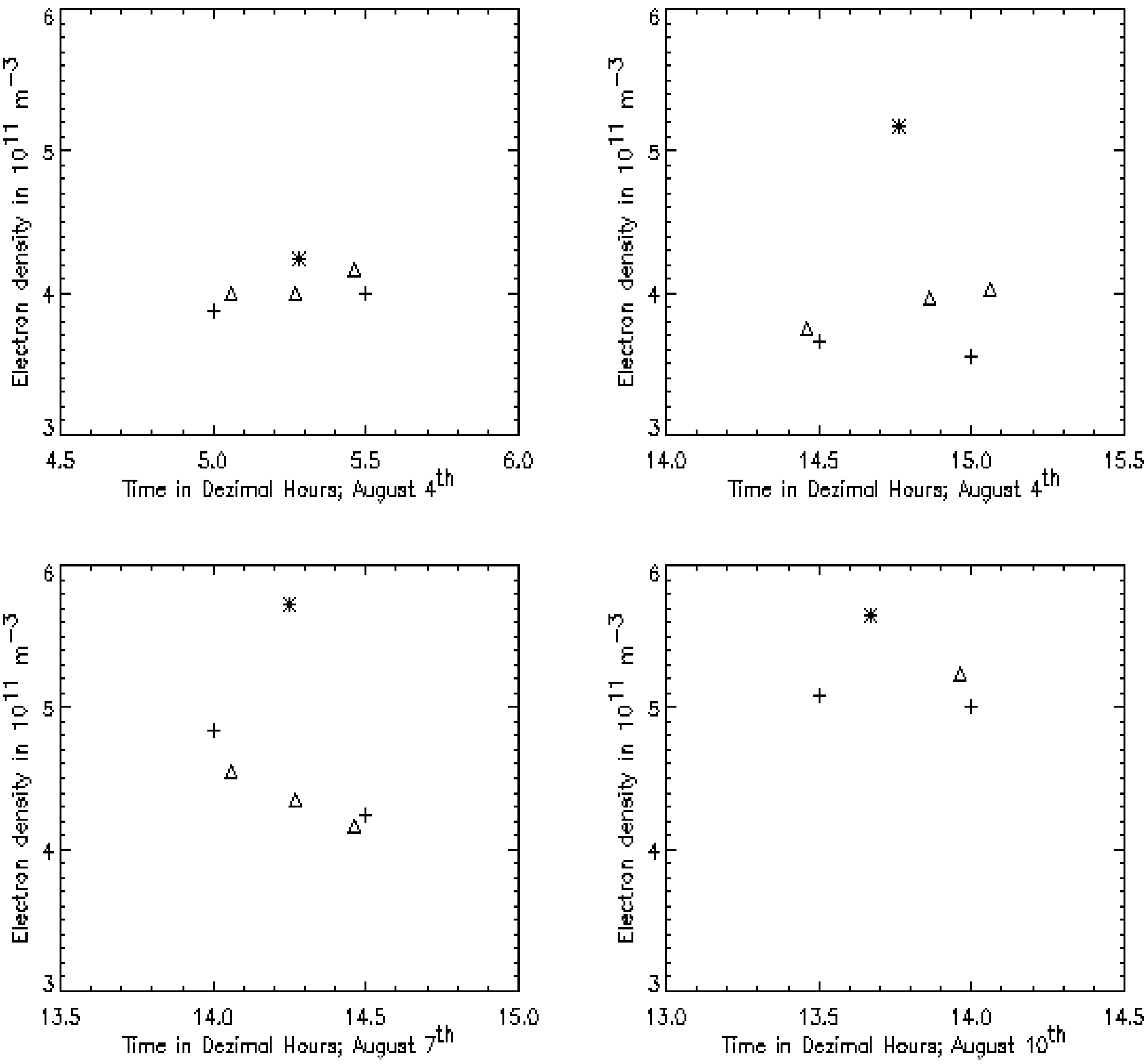

Figure 4: NmF2 measured by the Andøya (plus), the Tromsø (triangles) ionosonde and derived from CHAMP sounding (stars). The upper left panel presents event 1, the upper right one event 2, the lower left panel event 3 and the lower right one event 4.

The overestimation can be explained by the fact that all the ray path between GPS and CHAMP enters into the calculation of electron density profiling. Since CHAMP flies in a near polar orbit the occulting rays are south-north directed and therefore the crest region in equatorial latitudes with high electron densities influences the profiling.

Of course, in this study only a small number of selected occultations have been compared to ionograms. For reliable validation and statistics more events have to be considered.

Ionosondes in principle provide the possibility to derive electron density profiles from the bottom side of the ionosphere to the F2 maximium layer peak, which could also serve for comparison with CHAMP profiles. This, however, requires the reduction of virtual heights to real heights using the entire electron density profile, and for this in turn measurements to frequencies down to 1 MHz are necessary. At the time of the events, the Andøya ionosonde received frequencies of 4 MHz and higher only, so that we could not correct for the virtual heights and thus did not obtain the real profile, but only the peak electron density.

3. Conclusions

Temperature and electron density profiles derived from radio occultation measurements by the CHAMP satellite are compared with independent measurements at Andøya, Northern Norway. Three radiosondes have been released consecutive to validate a temperature profile from a radio occultation event of CHAMP at November 11, 2001. The occultation event occurred in a distance of 180 km during the time of the second balloon sounding. The direct comparison of the temperature profiles shows differences of –2 to +4 Kelvin in the height range 7-20 km. Above 8 km the CHAMP temperatures are in the whole range higher than the temperatures derived from the balloon sounding. The deviation of the vertical linear interpolation of the CHAMP profile increases with height by about 1.5-2 K/10 km. This seems to be due to a systematic bias of the mean value. The variation is in most of the region in the range of ±1 Kelvin around the mean deviation. This is smaller than the variability found by the precedent and subsequent balloon soundings. Since all measurements are performed during night conditions the daily variation does not account therefore. It may be stated that the variations of the CHAMP temperature lie within the range of local variations that are present during the occultation event. To reach the subkelvin range for the absolute temperatures with radio occultation measurements further improvement of the retrieval algorithm is necessary.

Comparing the NmF2 of CHAMP with the ionosonde measurements we may conclude that the values are in the same order of magnitude. However, a slight overestimation of the NmF2 has been found for the CHAMP results. This may be caused by including electron density structures over a large horizontal scale by the profiling technique. Taking into account some assumptions, as spherical symmetry that have been done for profiling with CHAMP data, the comparison shows fair results. Of course, more than one temperature profile and more electron densitiy data derived from radio limb sounding should be compared with independent measurements for reliable validation and statistics. However the cases discussed here give good outlook for further investigation.

Acknowledgments

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